Space Assembly and Service via Self-Reconfiguration

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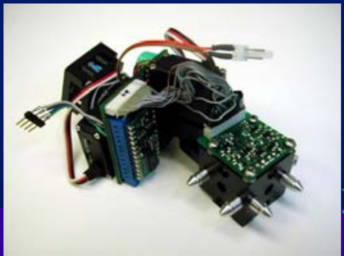
ISI Polymorphic Robotics Lab

http://www.isi.edu/robots

- Mission
  - To build ***Self-Reconfigurable Systems*** such as metamorphic robots, agents, and smart structures that go where biological systems have not gone before!!!
- Projects and Awards
  - YODA (1996) The 2nd place in AAAI competition
  - Dreamteam (1997) RoboCup World Champion
  - Intelligent Motion Surface in MEMS (1996-98)
  - CONRO Self-Reconfigurable Robots (1998-)
- People, Robots and Facilities
  - Experienced and talented research team
  - 3 Denny robots, 5 SoccerBots, 18 CONRO modls
  - Large labs and workshops, many instrumentations

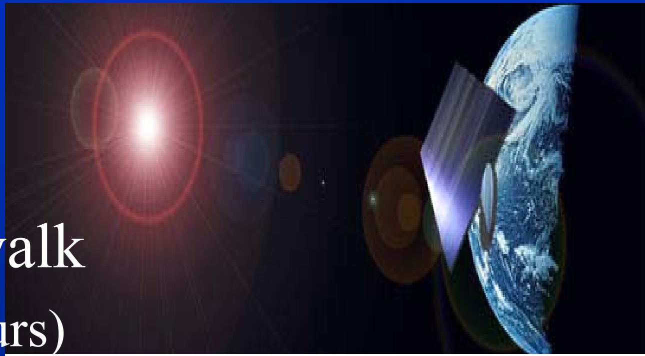


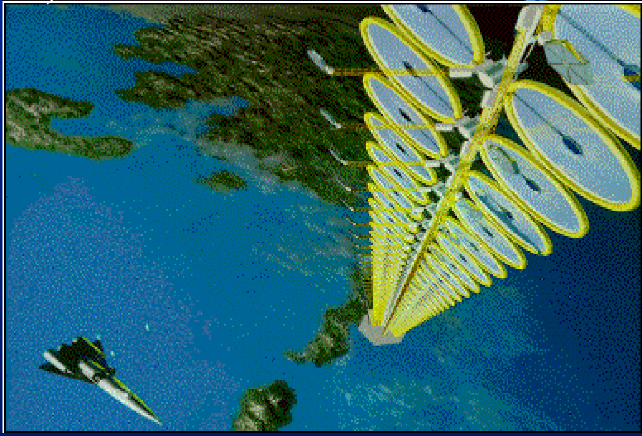
Outline

- Motivation for Self-Assembly in Space
- Three Enabling Technologies
  - Based on Self-Reconfigurable Robots
- Proposed Evaluation Experiments
- Research Plan for SSPS
- Future Directions

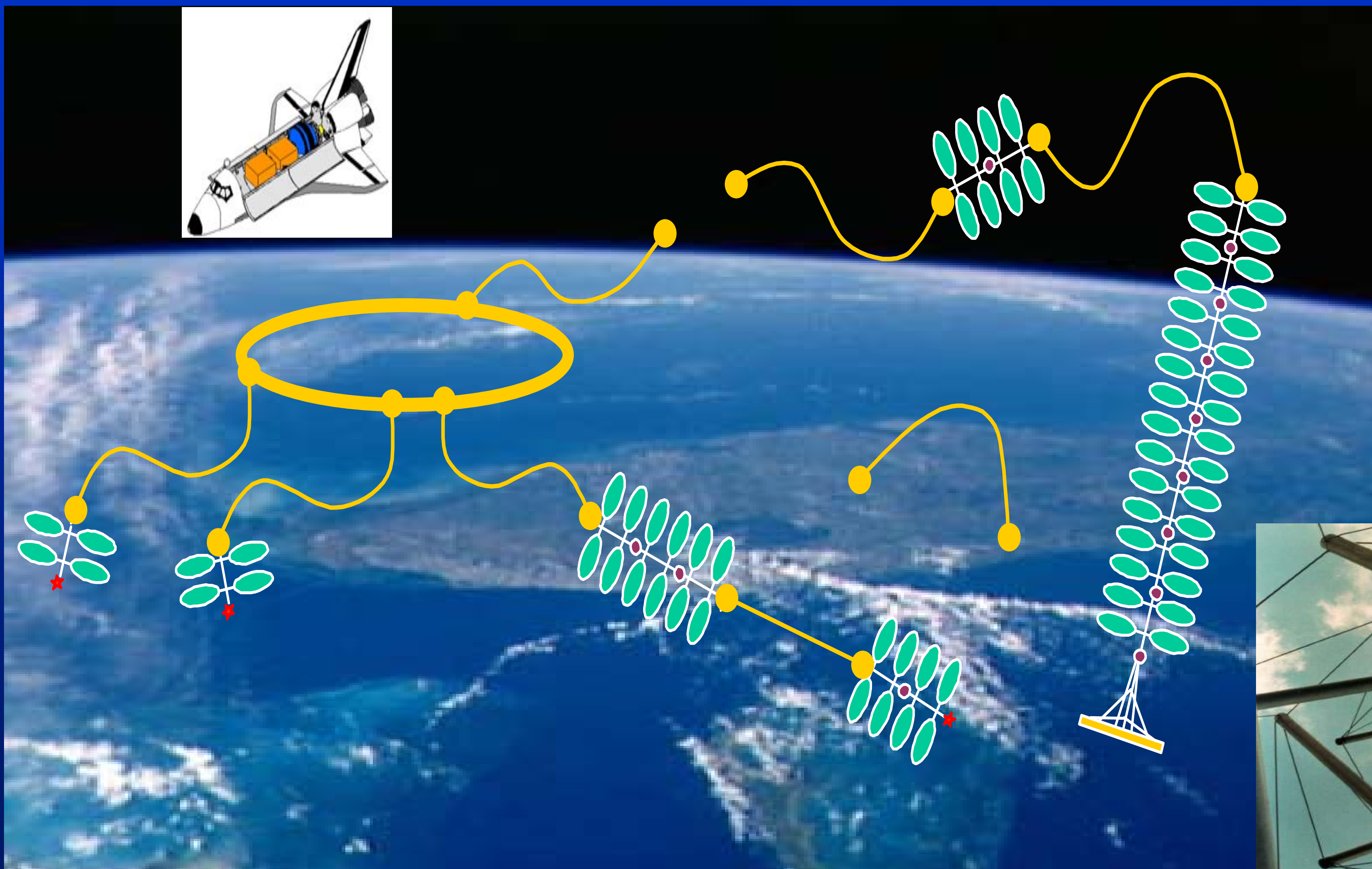
Motivation for Self-Assembly

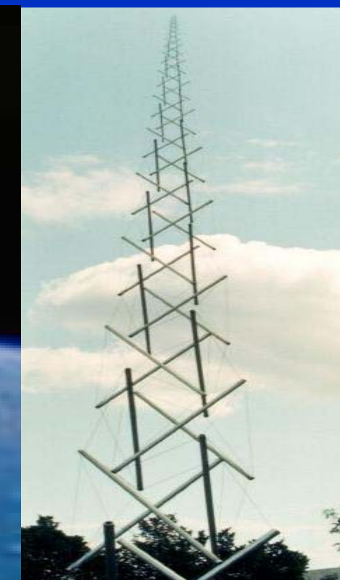
- Cost Effective
  - For a 10KM SSPS
    - >2,500 hours of astronaut space walk
      - 4/11/2002, girder assembly (2*6 hours)
    - >$3 billion for assembly cost
- Feasible Strategy
  - Most jobs by self-assembly
  - Critical jobs done by astronauts

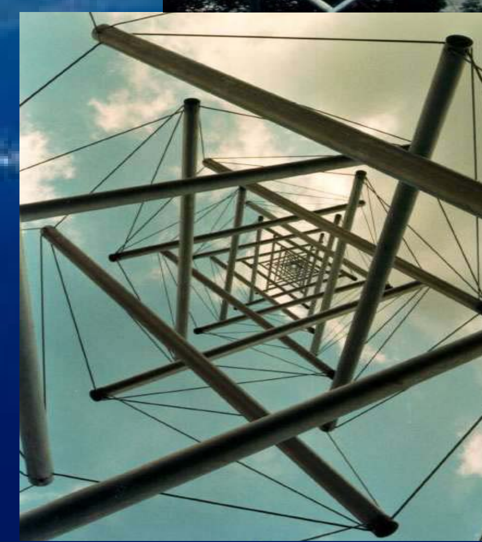




A Vision for Space Self-Assembly



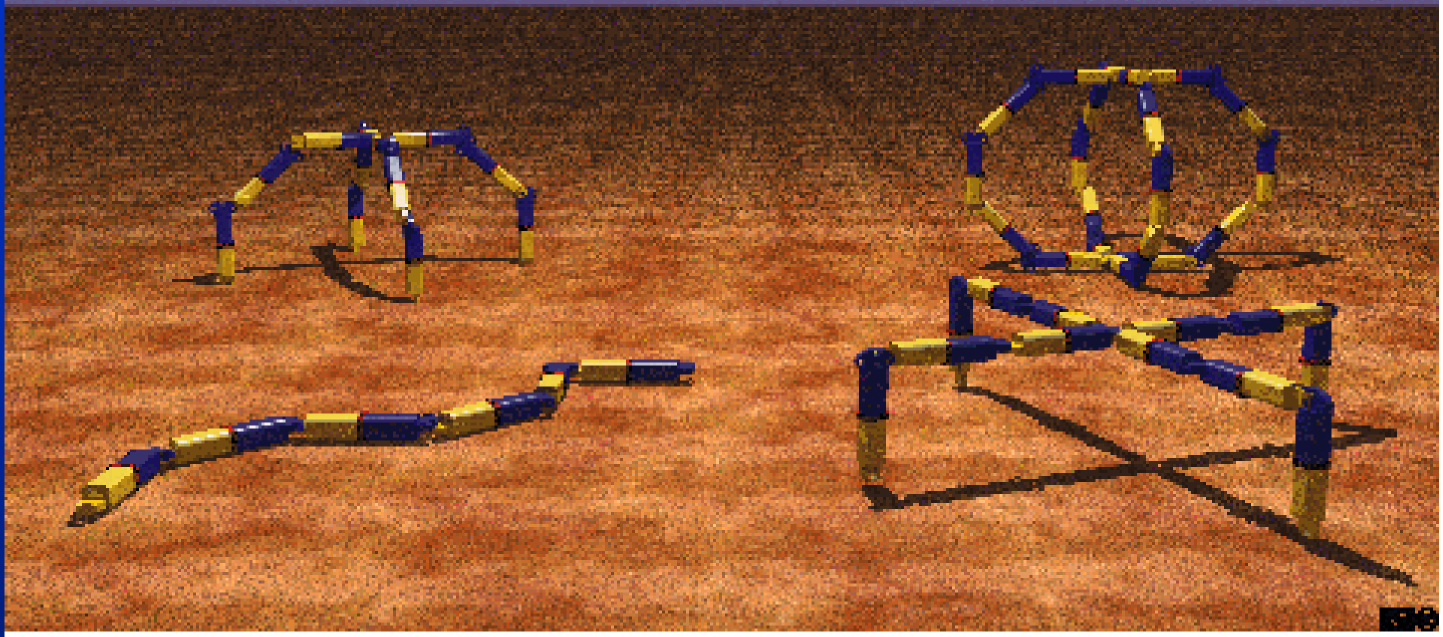


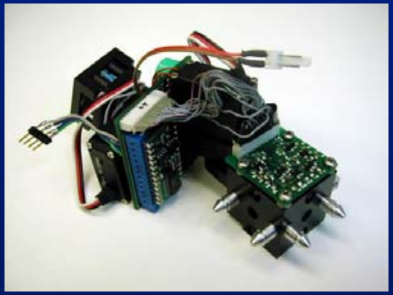


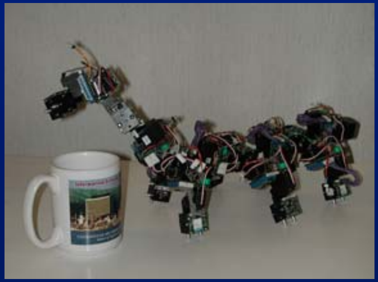
Three Enabling Technologies

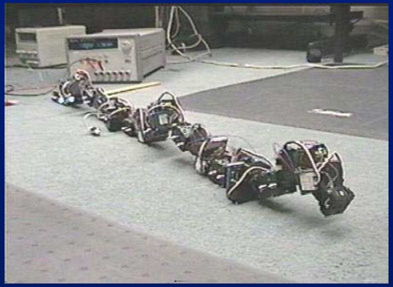
- Intelligent and Reconfigurable Component (IRC)
  - Can *free-float* and *dock* to form structures
- Free-flying Fiber Match-Maker Robots (FIMER)
  - Can *search*, *navigate*, *bring-together* and *dock* IRCs
- Distributed Process Controller (DPC)
  - Can *plan* self-assembly in a distributed manner and *recover* from unexpected situations

Self-Reconfigurable Robots





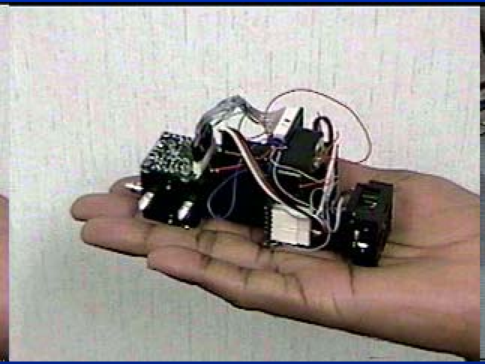


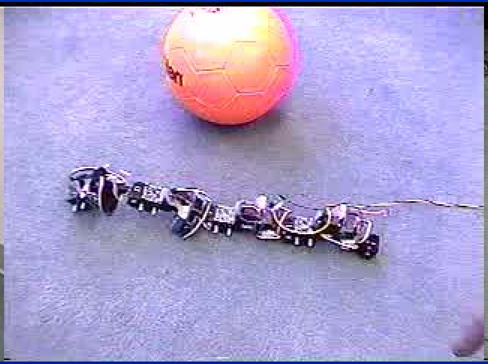


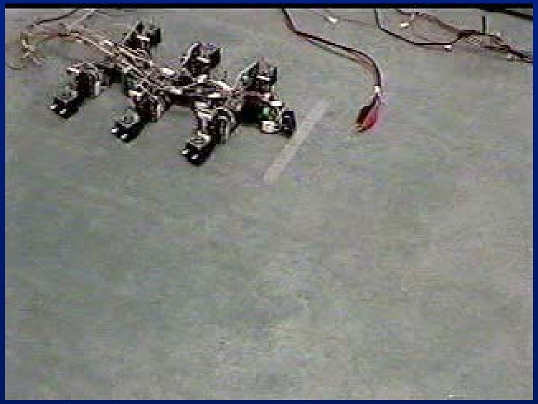
CONRO Self-Reconfigurable Modules

A network of physically coupled agents

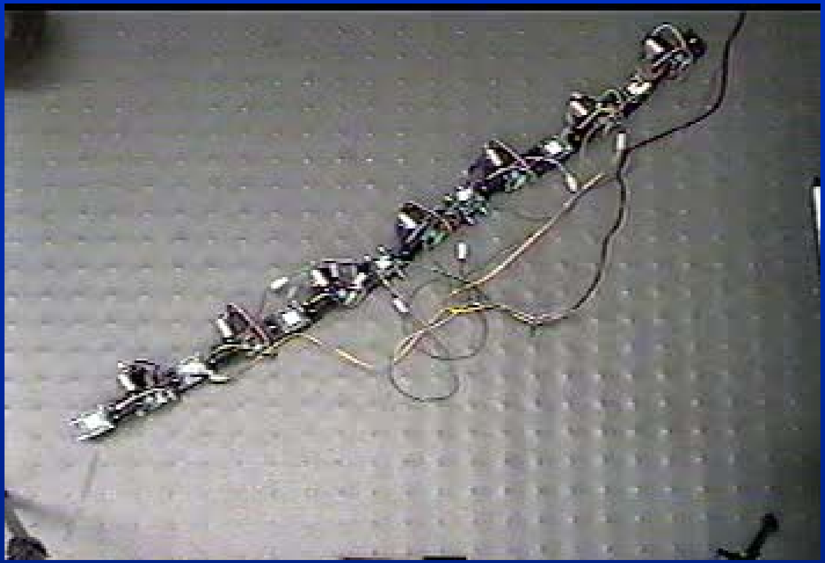
Self-assembling into various configurations!

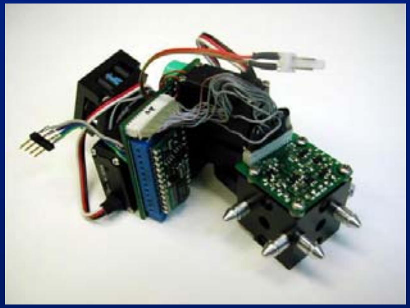


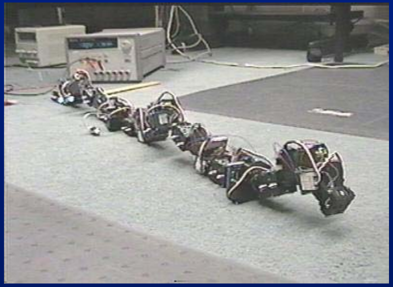




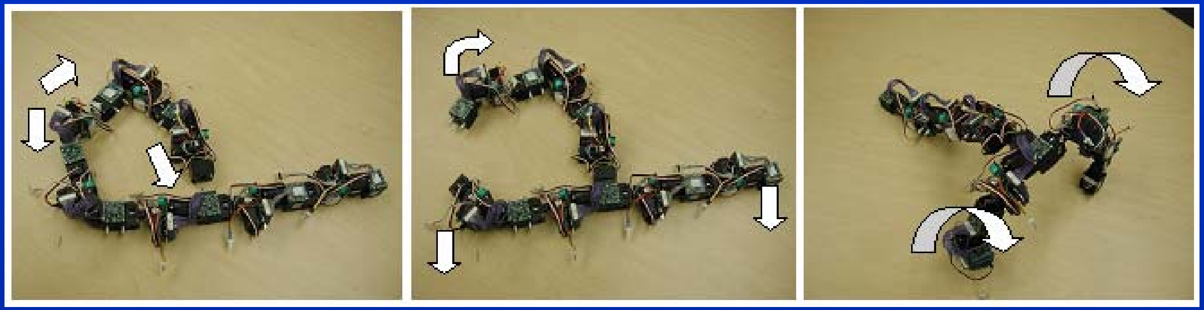
“Live Surgery” Reconfiguration







Beyond-Bio Self-Reconfiguration



Challenges in Control

- Distributed
  - Autonomous modules must be coordinated by local configuration information (no unique IDs or brain modules)
- Dynamic
  - Network and configuration topology changes
- Asynchronous
  - Communication with no real-time clocks, global or local
- Scalable
  - Weak local actions vs. grand global effects
- Fault-tolerant
- Miniature and self-sufficient

Related Work

- Self-Reconfigurable robots
  - Diffusion-reaction (Turing 52)
  - Cebots (Fukuda Nakagawa90)
  - Polybots (Yim 94)
  - Metrics (Chirikijan 98)
  - 3D structures (Murata '98)
  - Self repair (Murata 2000)
  - Molecules (Kotay&Rus '98)
  - Feather formation (Chuong '98)
  - Self-Transform (Dubowsky'00)

- Control approaches

  Control tables (Yim94)

  Multi-agents (Hogg2000)

  Finite State Machine (Rus2000)

  Decentralized and autonomous system (Mori84)

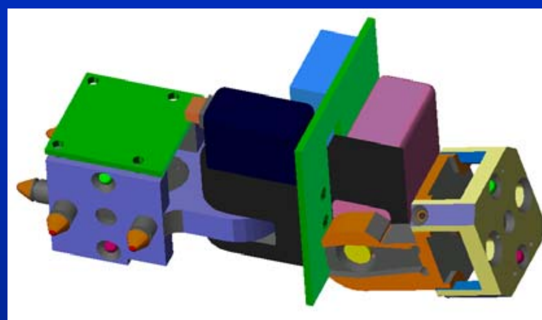
  Homeostatic control for resource allocation (Arkin88)

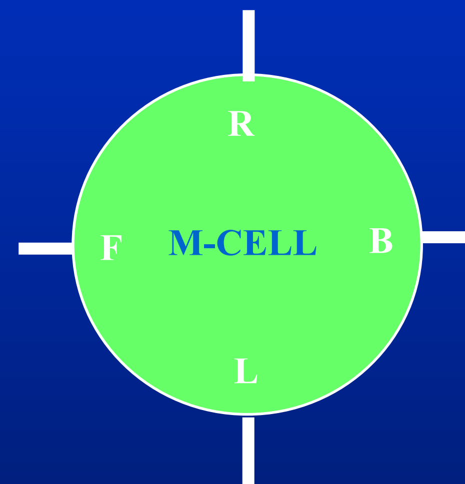
  Dynamic topology network (Si&Lin2000)

Digital Hormones

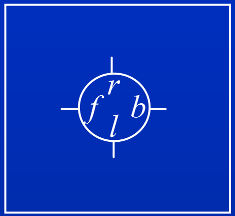
- Content-based messages
  - No addresses nor identifiers
  - Have finite life time
  - Trigger different actions at different sites
- Floating in a global medium
  - Propagated, not broadcast
  - Internal circulation, not external deposit (pheromones)
- Preserve local autonomy for individual sites
- Hormones can modify module behaviors (RNA)

Mechanical Cells (M-Cell)

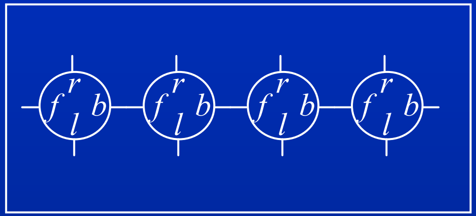




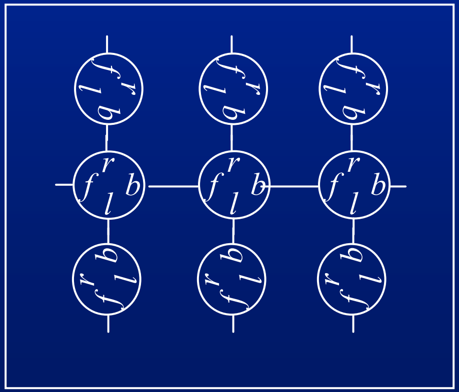
M-Cell Organizations



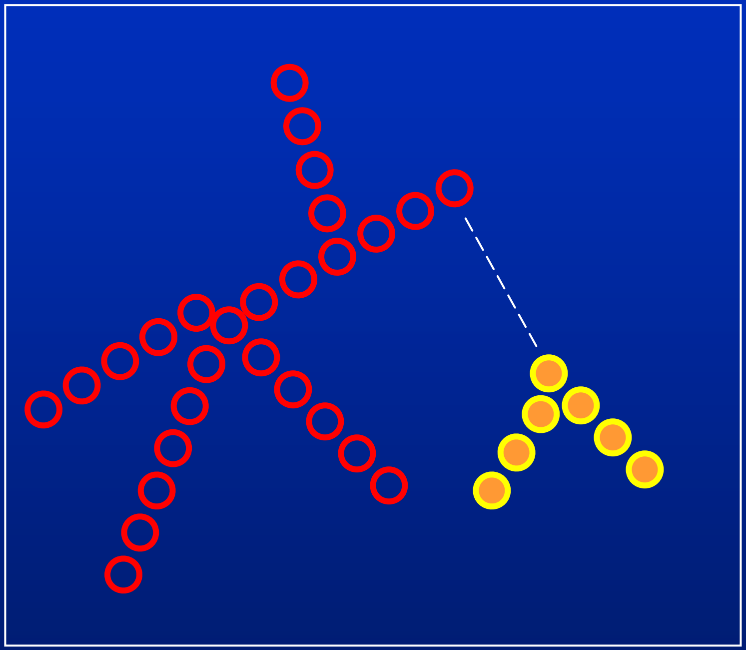
A module



A Snake

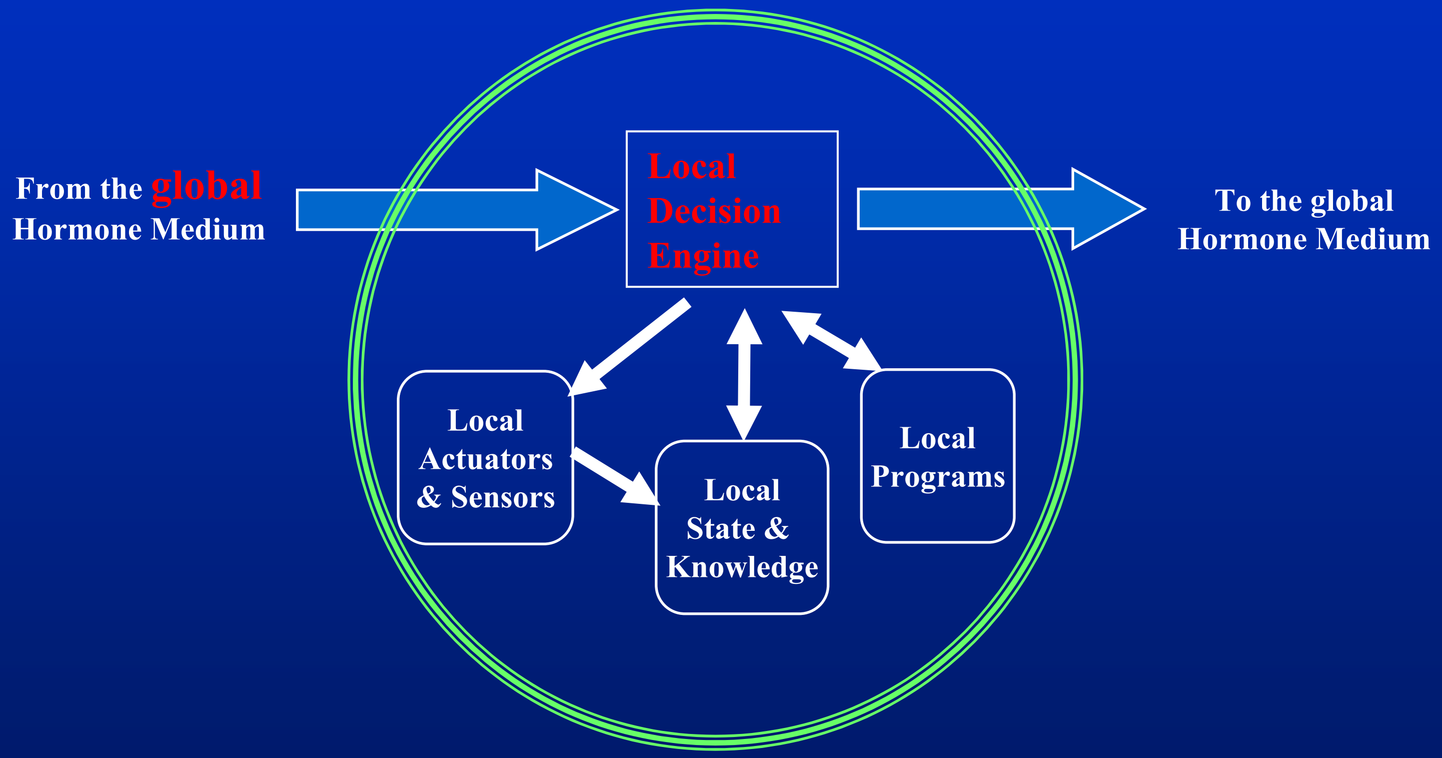


A 6-leg insect



Communication between two separate structures

M-Cell Control Software



Discovering Topology

Table 1: The Types of CONRO M-Cells

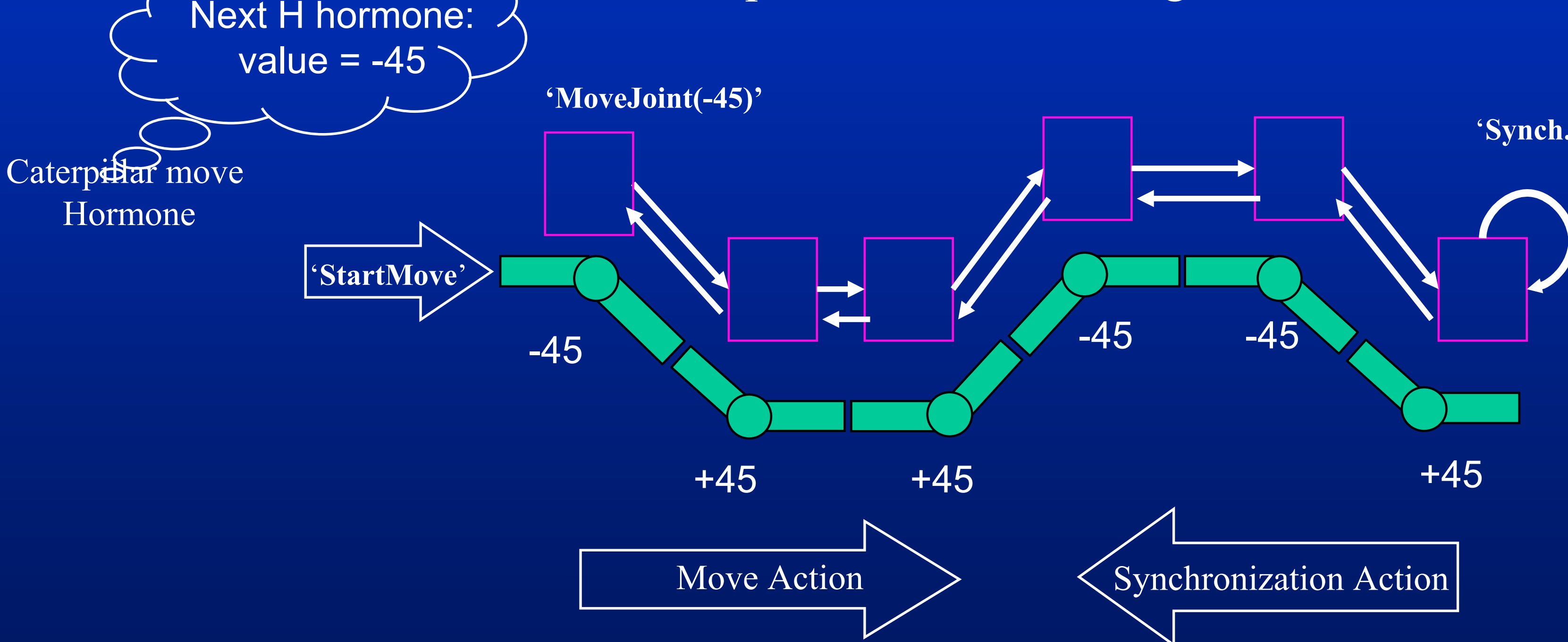
	This Module					This Module				
	b	*f*	*r*	*l*	Type	*b*	*f*	*r*	*l*	Type
Connected to other modules					T0	*f*	*b*			T16
	f				T1	*f*		*b*		T17
		b			T2	*f*			*b*	T18
			b		T3		*b*	*b*	*b*	T19
				b	T4	*f*	*b*	*b*		T20
	l				T5	*f*		*b*	*b*	T21
	r				T6	*f*	*b*		*b*	T22
		b	*b*		T7	*l*	*b*	*b*		T23
			b	*b*	T8	*l*		*b*	*b*	T24
		b		*b*	T9	*l*	*b*		*b*	T25
	l	*b*			T10	*r*	*b*	*b*		T26
	l		*b*		T11	*r*		*b*	*b*	T27
	l			*b*	T12	*r*	*b*		*b*	T28
	r	*b*			T13	*f*	*b*	*b*	*b*	T29
	r		*b*		T14	*l*	*b*	*b*	*b*	T30
	r			*b*	T15	*r*	*b*	*b*	*b*	T31

The Uses of Digital Hormones

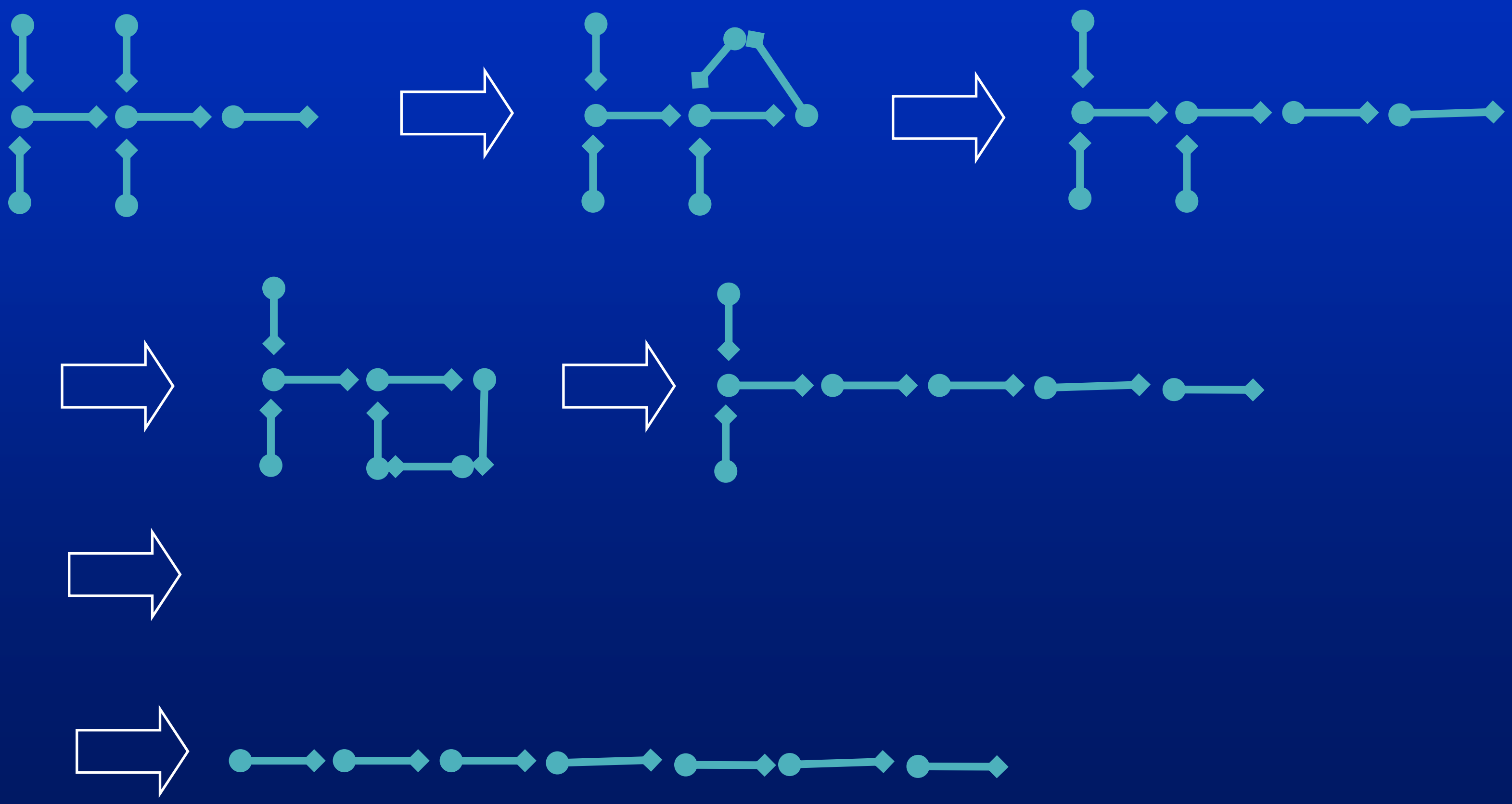
- Communication in dynamic network
- Cooperation among distributed autonomous modules
  - Locomotion
  - Reconfiguration
  - Synchronization
  - Global effects by weak local actions
  - Conflict resolution (multi hormone management)
  - Navigation
- Shape adaptation and self-repairing

Hormones for Caterpillar Move

- A simple one-pass hormone from head to tail
- Controls and synchronizes all motor actions
- Independent from the length of the snake



Reconfigure Insect → Snake

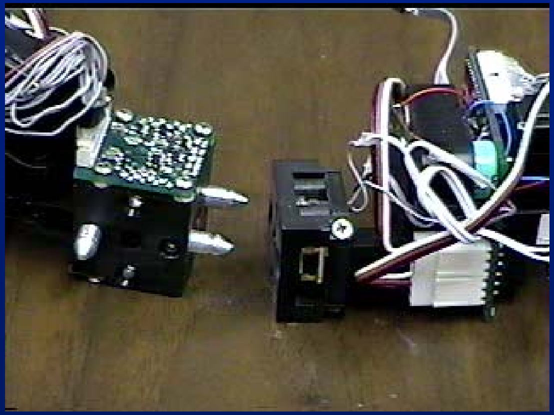
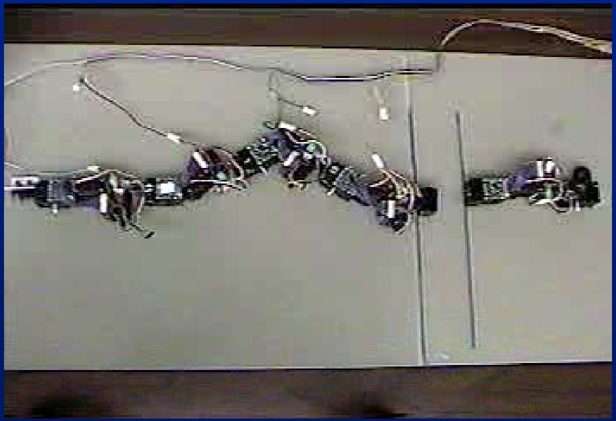


Hormone Activities

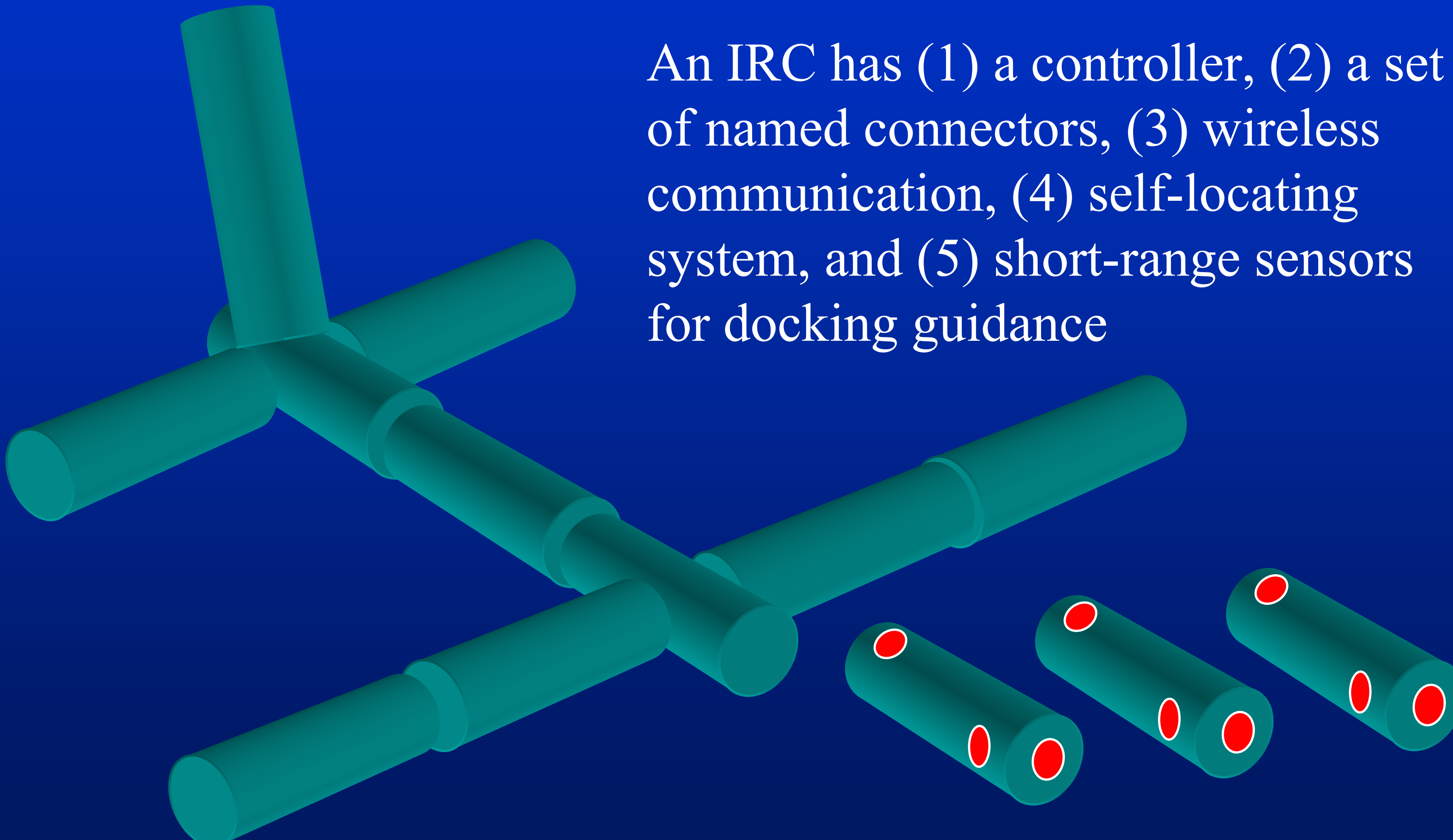
Active hormones	Actions
LTS	Start the reconfiguration
RCT_1, RCT_2, RCT_3, RCT_4	Legs are activated
TAR, RCT_2, RCT_3, RCT_4	The tail inhabits RCT, and leg1 determines RCT_1
ALT, RCT_2, RCT_3, RCT_4	The tail assimilates leg1 and then accepts new RCT
TAR, RCT_2, RCT_4	The tail inhabits RCT, and leg3 determines RCT_3
ALT, RCT_2, RCT_4	The tail assimilates leg3 and then accepts new RCT
TAR, RCT_2	The tail inhabits RCT, and leg4 determines RCT_4
ALT, RCT_2	The tail assimilates leg4 and then accepts new RCT
TAR	The tail inhabits RCT, and leg2 determines RCT_2
ALT	The tail assimilates leg2 and then accepts new RCT
∅	End the reconfiguration

Autonomous Docking

- A great challenge for self-reconfiguration
- Require precise sensor guidance
- Demand precision movement
- Complex dynamics in micro-gravity environment


Intelligent Reconfigurable Components



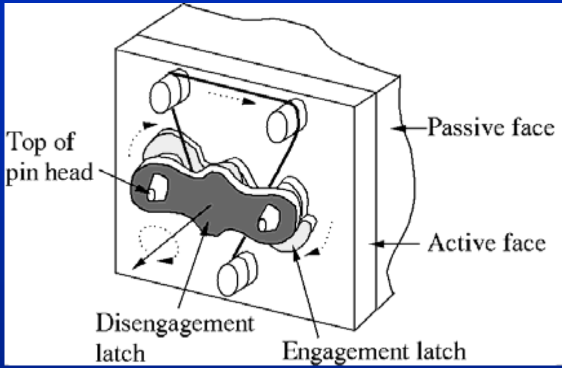
An IRC has (1) a controller, (2) a set of named connectors, (3) wireless communication, (4) self-locating system, and (5) short-range sensors for docking guidance

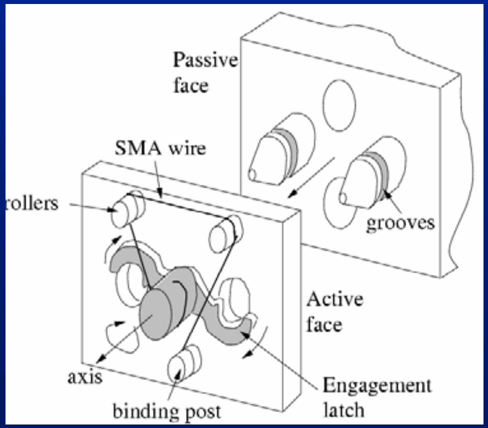
Reconfigurable Connectors

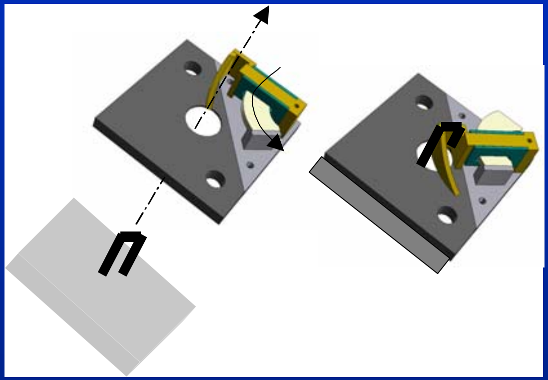
1999

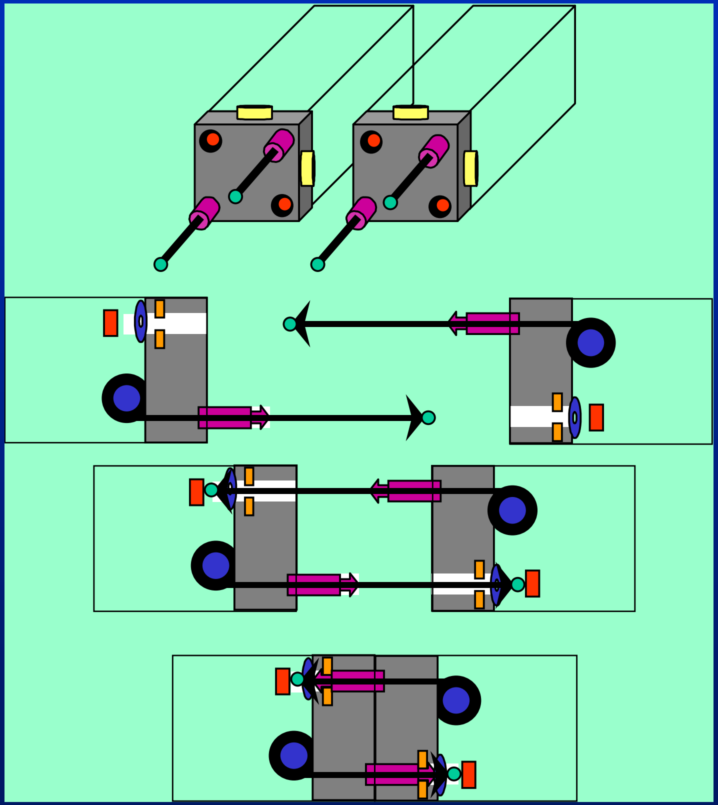
2001

2003



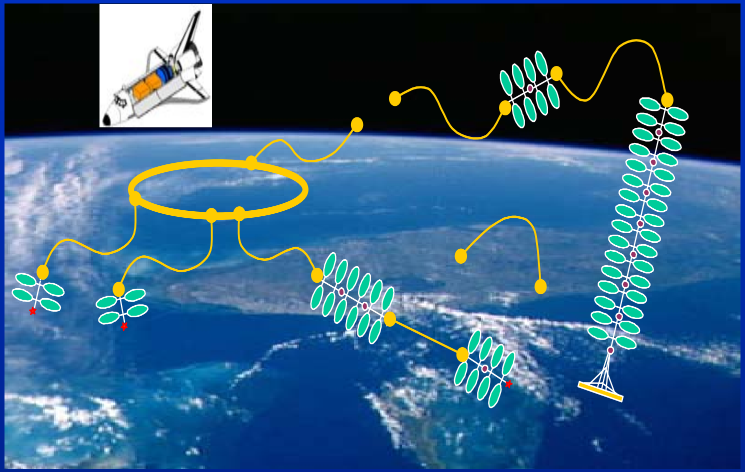


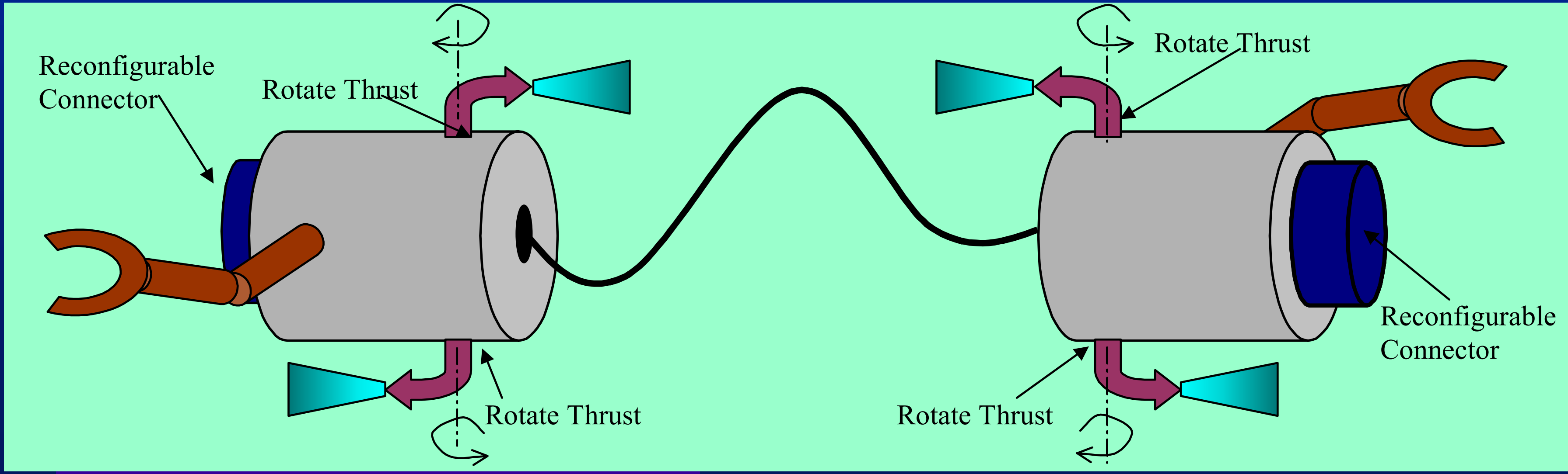




FIMER Robots

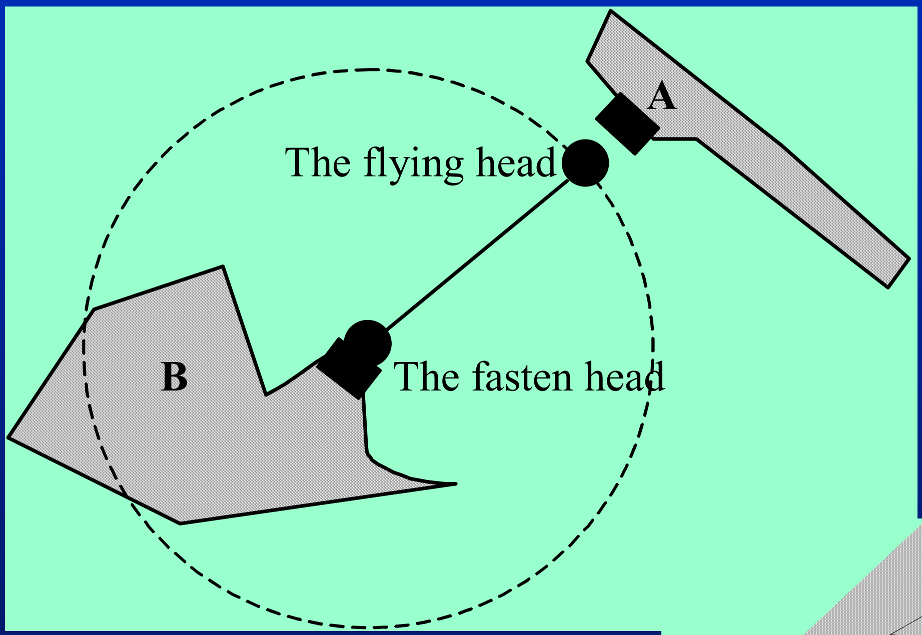
Two-headed fiber/rope
Free-flying head (6DOF)
Navigate and dock to the connectors
Rail-in fiber to bring parts together
Simple arms to assist dock
Onboard power or refuel capability





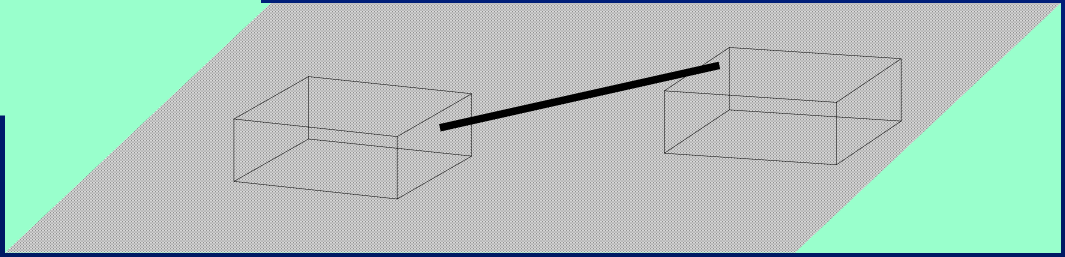
FIMER Dynamics and Control

Find relevant connectors based on their location information
Railing in the fiber only when there is no tension



Research Issues:

* Dynamics of tethered objects in zero-gravity environment
* Speed control
* Collision control
* Prevent tangling

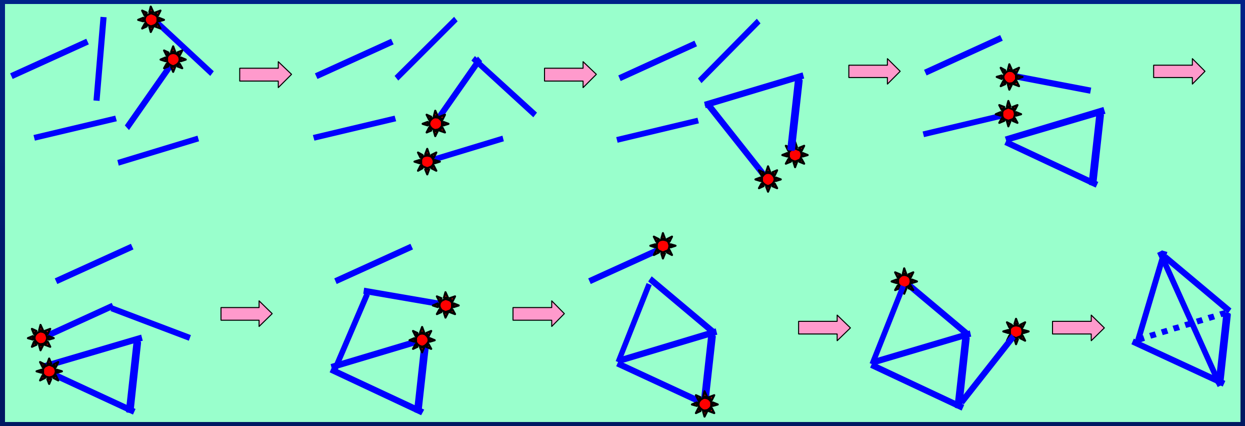


The Global Process Control

- How do modules know *when* and *where* to connect?
- Advantages for distributed control
  - Coordination of autonomous modules without fixed brain
  - Support dynamic configuration topology
  - Asynchronous: communication without global clocks
  - Scalable: support growing structures
  - Fault-tolerance
  - Self-repairing capability
  - Self-replanning for unexpected events

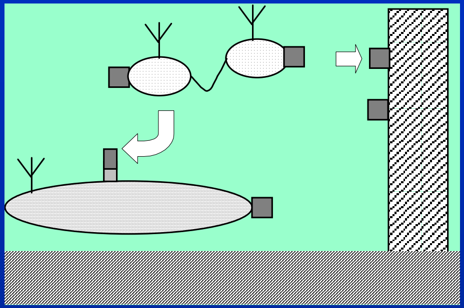
Proposed Process Control

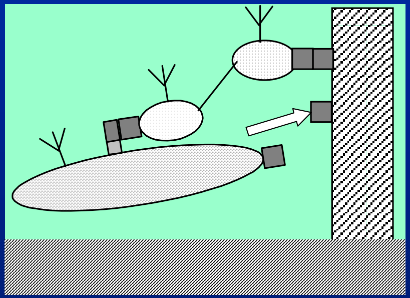
- Assumptions
  - Modules have unique identifiers
  - Assembly sequence embedded in modules
- Procedures
  - Activate self when receiving a call for its ID or type
  - Call FIMER robots to assist docking (when activated)
  - Activate the next connectors to be docked

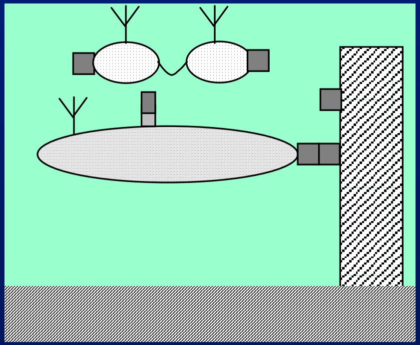


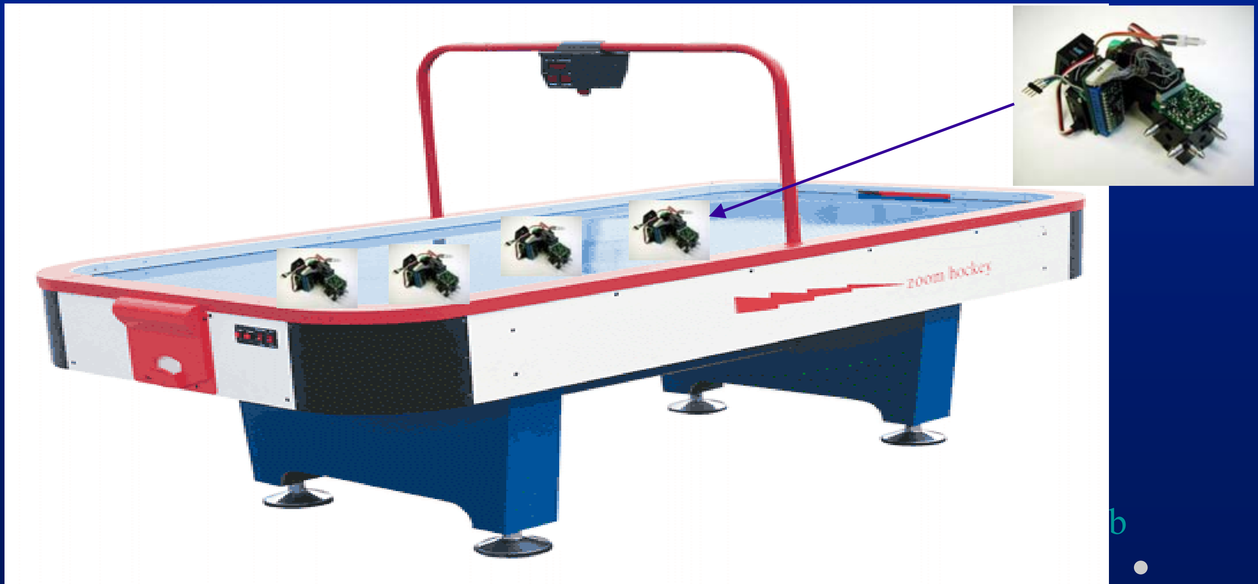
Proposed Experiments

- Build modules for autonomous planning, navigation, & docking
- “2D flight-test” on an air hockey table
- Extensible to future 3D flight-test in micro-gravity environment









Research Time Table

Task	Time
Computer Simulation	0-3 month
Building 2D flight modules/robots	0-12 month
Control framework and algorithms	6-24 month
Forming simple 2D structures	12-24 month